Pore-Level Modeling of Geologic Sequestration in Porous Media:

When does the injected carbon dioxide exhibit fractal fingering vs. piston-like displacement?

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Abstract

Over the next century, a vast quantity of CO_2 will need to be sequestered. To understand how to increase the available storage capacity in geologic formations, we have developed a pore-level model of displacing water in porous media with CO_2. For a variety of realistic CO_2 viscosities (corresponding to pressures and temperatures at various depths), we have increased the capillary number (or injection rate) and studied when the flows cease being fractal, characterized by fingered displacement fronts, and become linear, with smooth, piston-like displacement. Saturation profiles of the CO_2 for several viscosities and capillary numbers are presented. Results suggest improved equations for CO_2-water flows in geologic sequestration simulators.

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The effect of the fluid properties (viscosity and surface tension) on the carbon dioxide sequestration is the primary focus of this work.

In this presentation, we will

i) describe the pore level model

ii) present results for several viscosity ratios ($M=\mu_{injected}/\mu_{displaced}$) & capillary numbers

$$\left(N_c = \frac{\text{viscous forces}}{\text{capillary forces}} = \frac{\mu V}{2\,\sigma\cos\theta}\right)$$

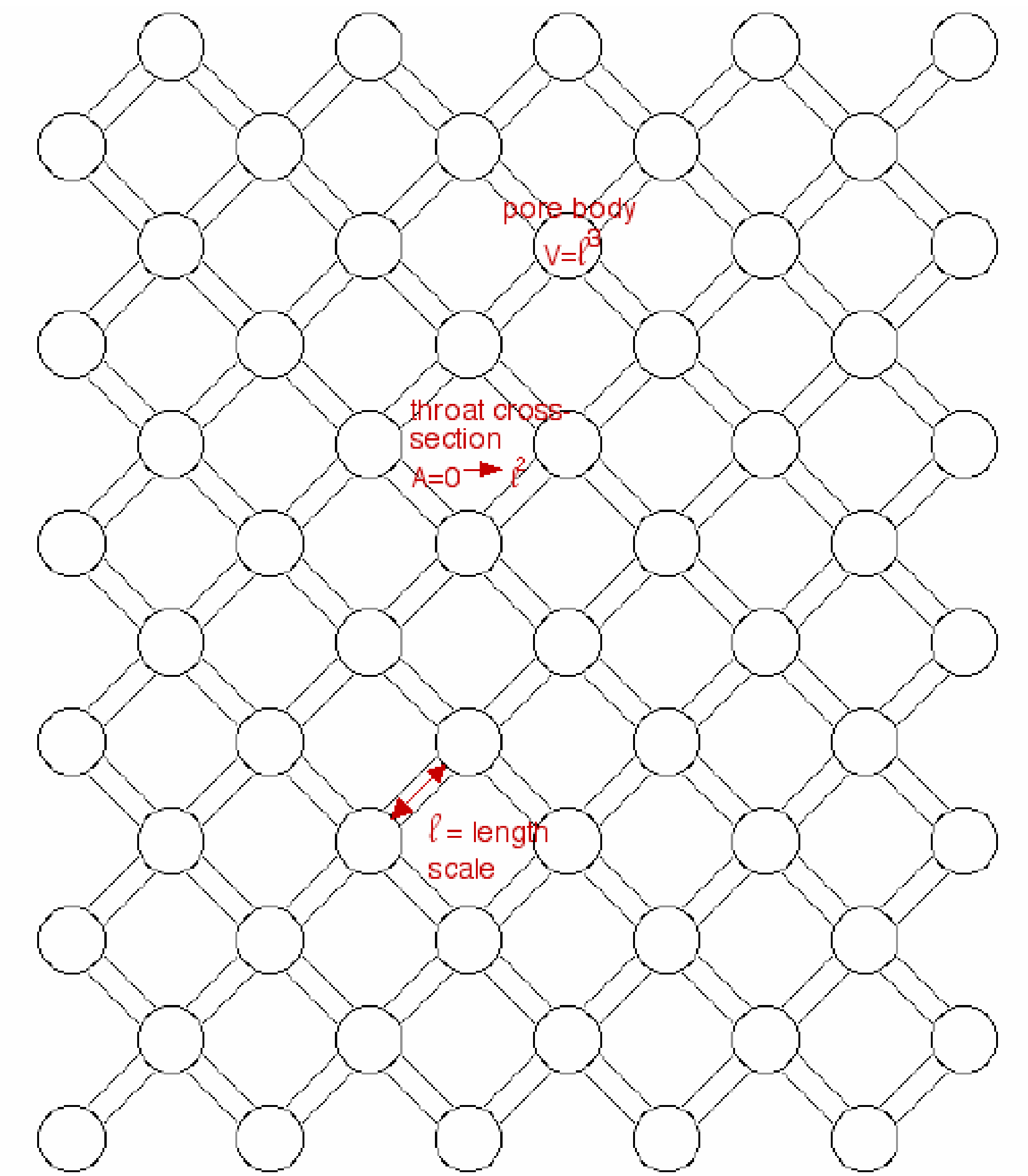
a) the flow patterns

b) the saturation profiles at breakthrough

c) the breakthrough saturations

iii) describe crossover from fractal to piston-like displacement

Description of the Model



In the model, throats of randomly chosen cross-section ($0<A<\ell^2$) connect pore bodies of volume ℓ^3.

The model includes both viscous and capillary forces.

Capillary Pressures $\approx$ r^{-1}

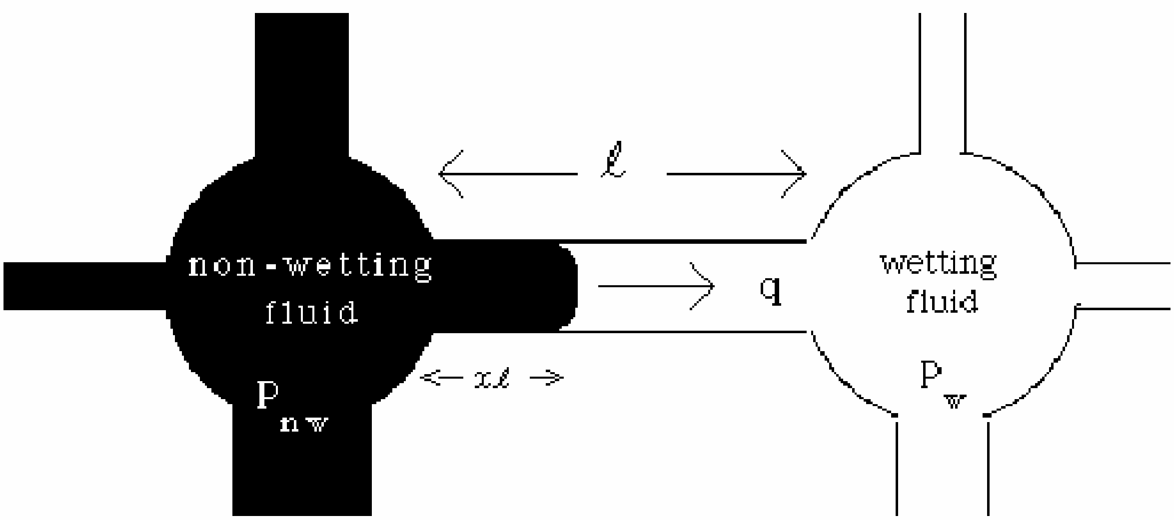
$$P_{cap}(R) = \frac{2\,\sigma \cos\theta}{r_{throat}}$$

Flow velocities $\approx$ conductance $\times$ Pressure Drop

$$q = g_{throat}\,(P_{nw} - P_{w} - P_{cap})$$

$$g_{throat} = g^{*}\,\frac{(r_{throat}/\ell)^4}{(x+(1-x)M)}$$

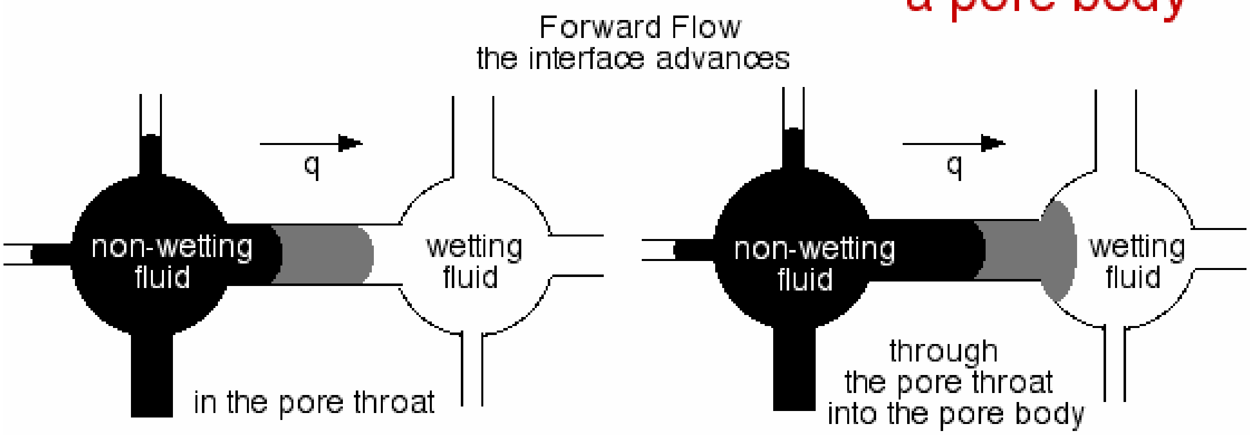
M is the ratio of the viscosities $M = \mu_{nw} / \mu_{w}$



The fluid is advanced through a small time Δt using non-restrictive flow rules

The invading (non-wetting) fluid can advance

in a throat | through a throat into a pore body



The invading (non-wetting) fluid can also retreat within a throat and through a throat into a pore body

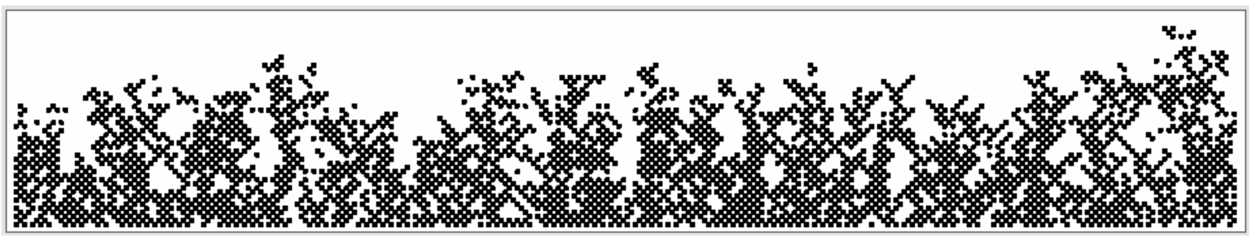
The flow patterns and saturation profiles at breakthrough are shown below for several capillary numbers and viscosity ratios.

These show the characteristic fractal behavior for the smallest viscosity ratio, M=1/40, but change over to the familiar linear behavior as the viscosity ratio increases.

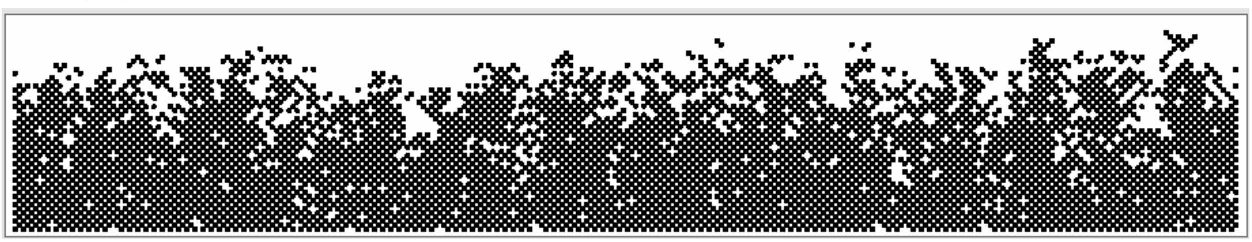
The Breakthrough Flow Patterns for N_c=0.1 are

M=1/40

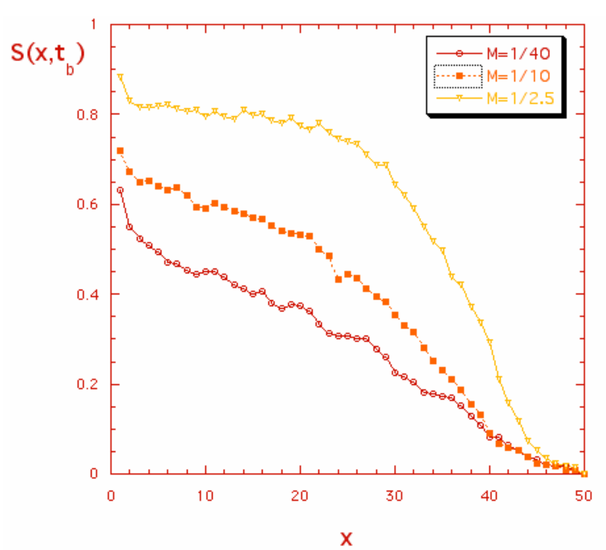
M=1/10



M=1/2.5

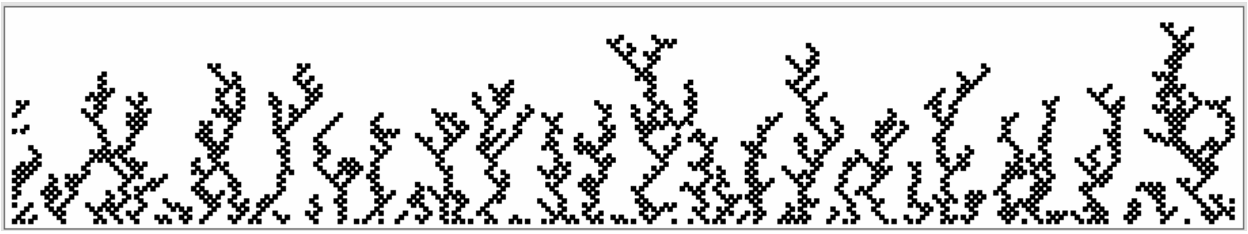


The breakthrough Saturation Profiles for N_c=0.1 are

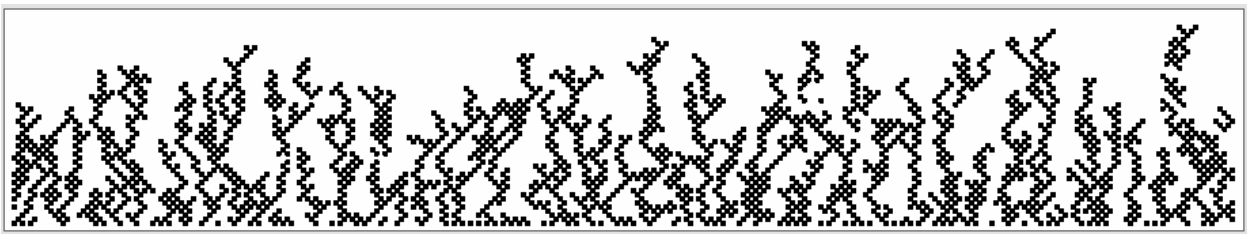


The Breakthrough Flow Patterns for N_c=0.016 are

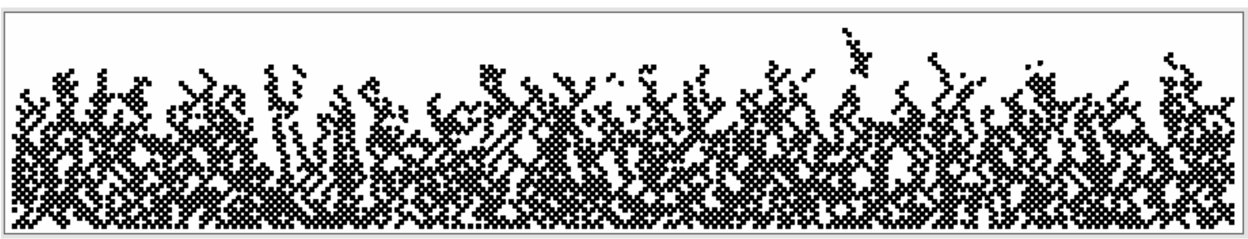
M=1/40



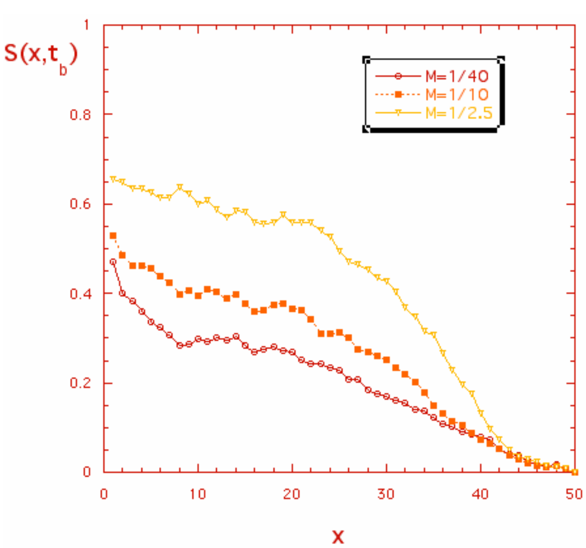
M=1/10



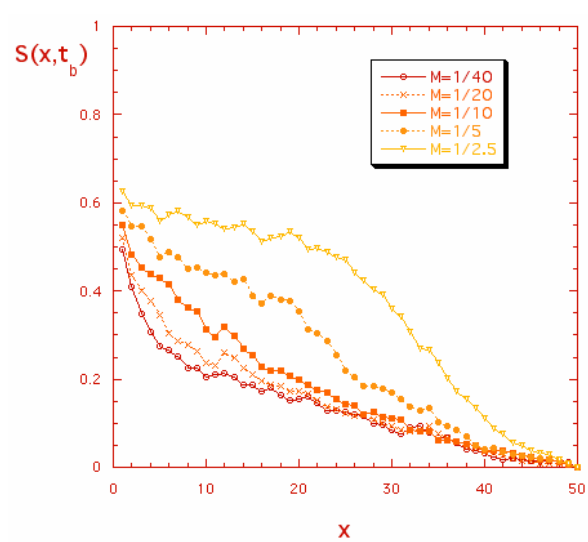
M=1/2.5



The breakthrough Saturation Profiles for N_c=0.016 are



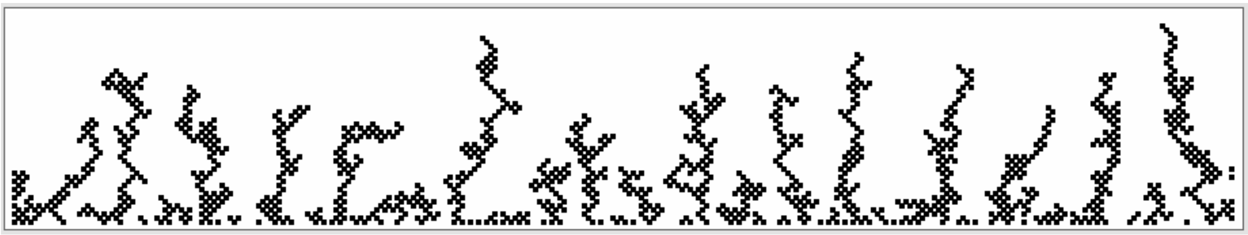
The breakthrough Saturation Profiles for N_c=0.004 are



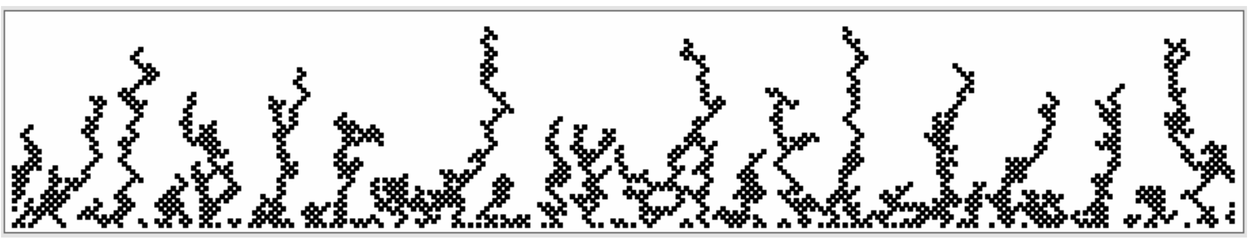
The Breakthrough Flow Patterns for N_c=0.004 are

M=1/40

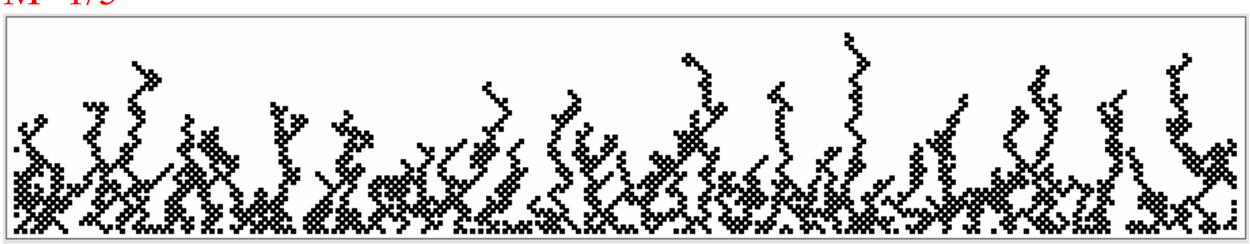
M=1/20



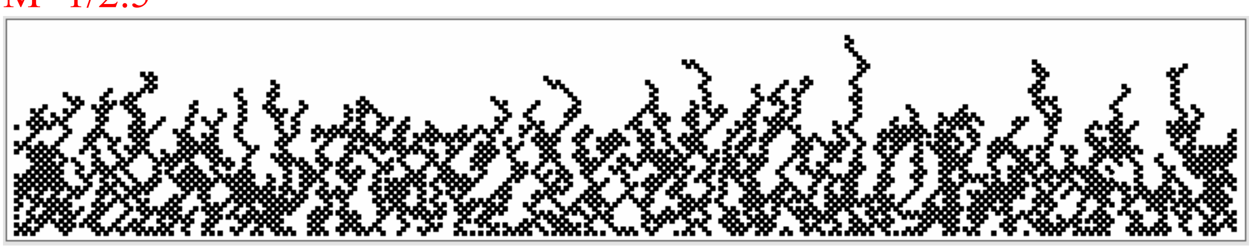
M=1/10



M=1/5

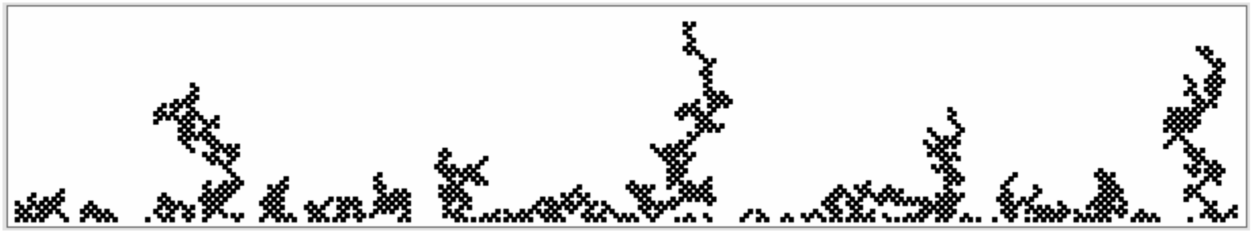


M=1/2.5

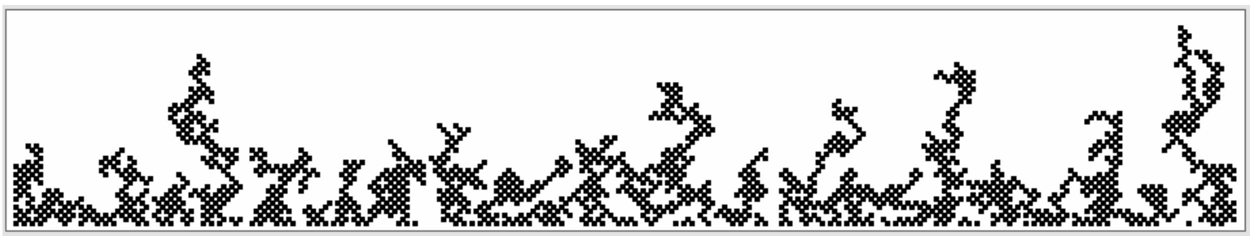


The Breakthrough Flow Patterns for N_c=0.001 are

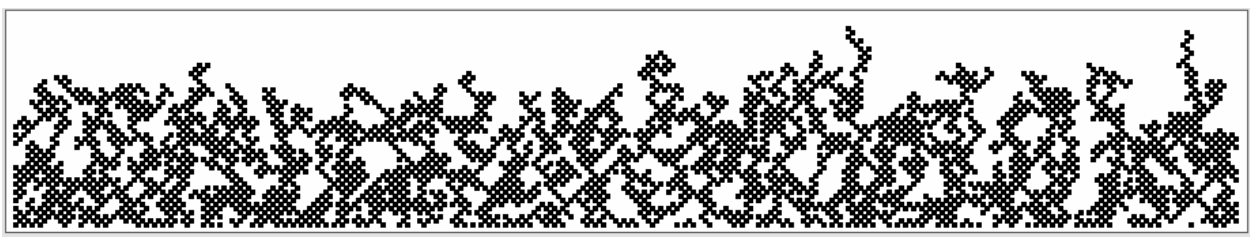
M=1/40



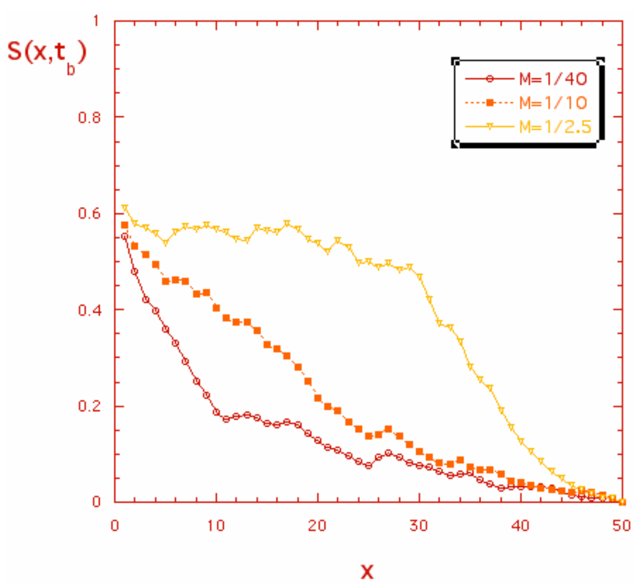
M=1/10



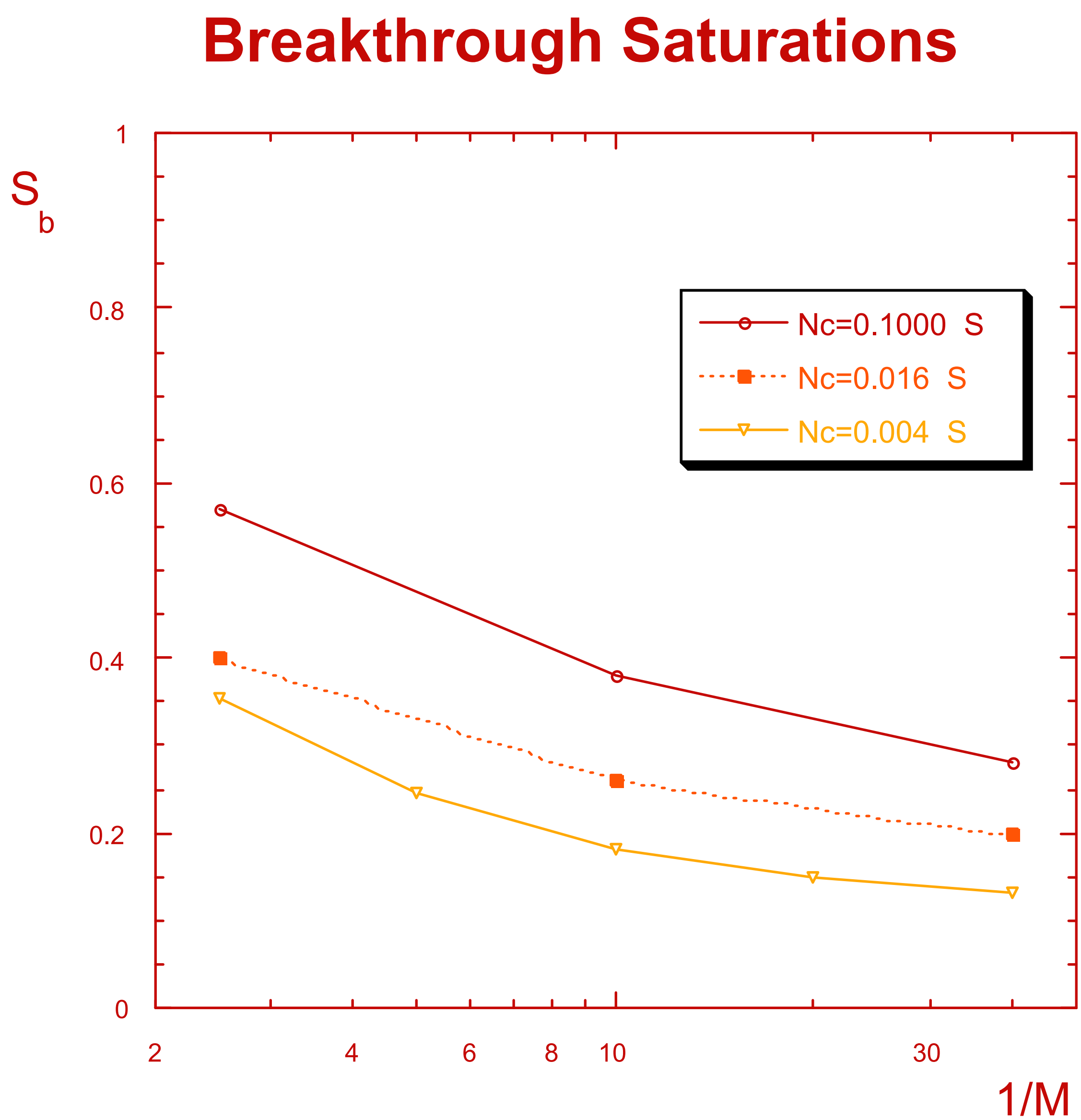
M=1/2.5



The breakthrough Saturation Profiles for N_c=0.001 are



The breakthrough saturations are shown for a variety of capillary numbers & viscosity ratios.



The breakthrough saturations increase with capillary number and viscosity ratio.

Crossover

from

fractal behavior,

where fingering causes the center of mass
to advance faster than linearly,

$$\langle x \rangle = A\, t^{1.4},$$

to

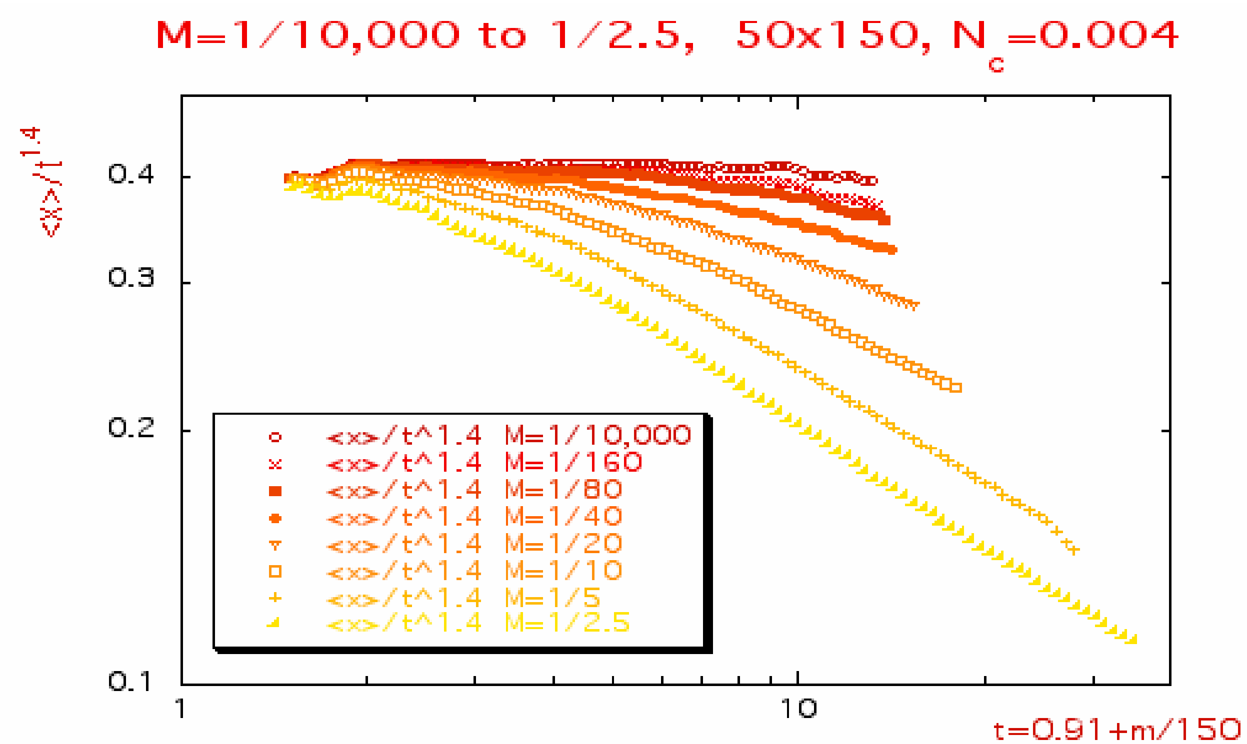
the familiar **linear behavior**

where the center of mass advances linearly,

$$\langle x \rangle = v\, t,$$

is demonstrated below for capillary
number $N_c = 0.004$.

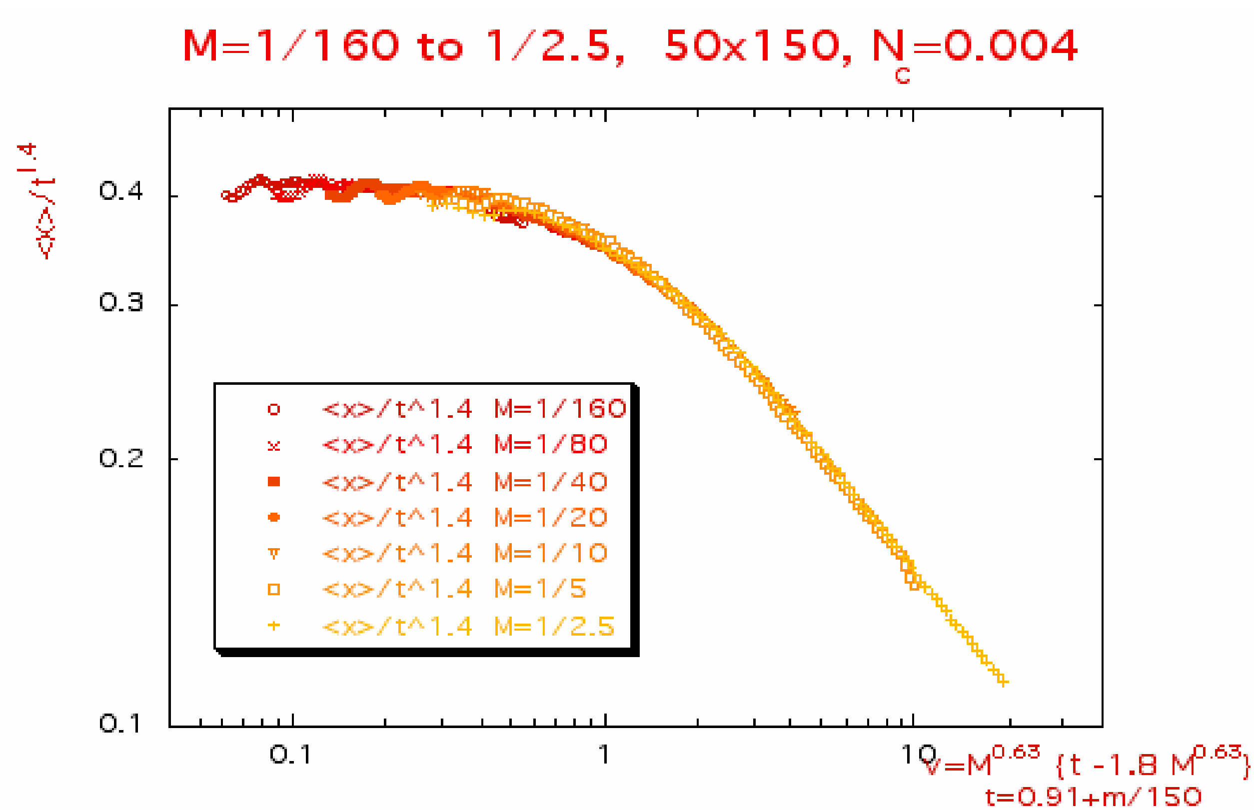
In this figure, $\langle x \rangle / t^{1.4}$ is plotted vs. t. For fractal behavior, $\langle x \rangle / t^{1.4}$ will be constant, i.e. A; for linear behavior, $\langle x \rangle / t^{1.4}$ will decrease like v $t^{0.4}$.



For early times, the center of mass position $\langle x \rangle$ obeys the characteristic fractal behavior, $\langle x \rangle / t^{1.4} = A$, for all viscosity ratios, but then, at later times, it breaks away and obeys the familiar linear behavior $\langle x \rangle / t^{1.4} = v / t^{0.4}$.

Viscosity Ratio dependence of the Crossover

This figure shows that the viscosity ratio dependence of the crossover is accounted for by a re-scaling of the time.



For Nc=0.004,

$$<x> = t^{1.4} \chi(M^{0.63}\{ t -1.8 M^{0.63}\}) .$$

Conclusions

i) We have observed this crossover at all non -zero capillary numbers.

ii) Therefore, any flow will show early-time fractal behavior, but then crosses over to the familiar linear behavior.

iii) We have shown that a rescaling of time accounts for the viscosity ratio dependence of the crossover at one value of N_c. We will extend this to the full range of capillary numbers.

iv) It has been shown that this 'cross-over' can lead to definite predictions for the dependence of the usual flow parameters (saturations, fractional flows, and relative permeabilities) on viscosity ratio and capillary number. These predictions will lead to improved equations for CO_2-water flows for use in geologic sequestration simulators.